(1) Research and understand the design specifications and operational use of the system under test. Use this knowledge to define the parameters critical to assessing the performance of the system and also as a means for calculating the theoretical boundaries of the system's performance.
(2) Precisely define the purpose of the test procedure to include the parameters to be measured during the test.
(3) Define the data necessary to calculate the parameter under test and assess the instrumentation requirements necessary to measure the data.
(4) Outline the detailed procedure necessary to perform the data collection effort.
(5) Define the analysis necessary to take the measured data and calculate or assess the parameter under test and then decide upon the proper presentation format to document the parameter.
(6) As a last effort, generate data cards that provide an outline of all information necessary to perform the data collection effort and record the results.[3]

2.0 AIR-TO-AIR AND AIR-TO-GROUND RADAR SYSTEMS TESTING

2.1 Introduction to Radar Theory

2.1.1 General

Radar (Radio Detection And Ranging) was first used operationally in 1937. This rudimentary system included a simple pulsed scheme to determine target bearing and range. [Ref. 9:p.1]. The first successful airborne radar was the Al Mark IV carried on the Bristol Beaufighter 19 in 1940 which used simple pulsed techniques to determine airborne target range [Ref. 56:p.2]. From these humble beginnings, radar has developed to the point that it has become the centerpiece in virtually every modern airborne weapon system. In the very simplest terms, a radar sends into space a Radio Frequency (RF) pulse of known characteristics, waits for the waves reflected off the target to return and analyzes the characteristics of the returned wave to derive information about the reflecting target [Ref. 39:p. 2.1].

2.1.2 Pulsed Radars

The simplest of radars are the pulsed radars. The operating principles of pulsed radars are based on the fact that RF energy propagates through space at a constant velocity. This velocity, strictly speaking, is applicable only in a perfect vacuum and is altered slightly by the atmosphere. Propagation velocity is a function of transmission frequency, and atmospheric molecular composition, temperature and pressure. The speed of propagation increases slightly at higher altitudes [Ref. 11:p. 81]. This effect is small; however, at the ranges and frequencies discussed in this section. For airborne test purposes, a "radar mile" of 12.36 microseconds can be defined, which is the time required for RF energy to travel out one nautical mile (nm) and then return [Ref. 27:p. 1-4.2].

The basic components of a pulsed radar include a transmitter, receiver, two antennas and a display [Ref. 60:p. 4]. Two antennas are included because the system requires a transmit antenna and receive antenna. In practice, a single antenna is time shared for both purposes. A duplexer is used to switch between the transmit and receive sides of the radar. The transmit side is connected only when actually firing a pulse and the receive side is connected to listen for returned pulses. [Ref. 56:p. 4]. This scheme prevents the transmit pulse from being directed to the receive side of the radar.

Transmitter antennas are usually designed to concentrate the transmitted pulse in as narrow a beam as possible. Similarly, receiver antennas are designed to receive signals within the same narrow beam. This phenomenon of essentially equal performance of the antenna in both transmit and receive modes is known as reciprocity and can be useful in designing tests [Ref. 36:p. 2.132].

[3]Refer to chapter 6 for a discussion of how to combine all the various tests, and their data cards, into an intelligent flight plan.

The antenna beam width is usually defined at the 3 decibel (db) power drop off points each side of the radar antenna boresight and is usually measured both horizontally and vertically [Ref. 36:p. 2.135a, Ref. 27:p. 3-1.1, Ref. 21:p. 66]. Beam width is critical since it is through this characteristic that the direction to a target is determined. As the antenna is scanning, or moved in a search pattern, the antenna pointing angle with respect to the aircraft is measured. The rate of antenna movement is insignificant when compared to the RF propagation speed. Thus the relative angle at which the radar antenna is pointing when the signal is sent out, reflected and returned, is the angle to the target. [Ref. 39:pp. 2.8-2.9]. The angle to the target is determined both horizontally and vertically. Target angle determination errors can be incurred due to the beam width of the antenna and to inaccuracies in the measurement of the antenna pointing angle. It must be noted that some modern radars can provide azimuth resolution better than the antenna beamwidth. With the exception of doppler beam sharpening, to be discussed in the air-to-ground radar section, these technologies will not be covered in this document; however, the test techniques are similar.

Antenna beam width also determines the minimum angular resolution of the radar. When two targets are at the same range from the radar, they must be separated by at least the antenna beam width to be distinguishable as two targets. Since the returned radar pulses from the two reflecting targets will arrive at the antenna face simultaneously and will thus be unresolvable without additional information (which will be discussed later). [Ref. 39:pp. 2.9-2.10]. Air-to-air radar antennas generally strive for small horizontal and vertical beam widths because this improves both the vertical and horizontal angle determination of airborne targets. Air-to-ground radar antennas use small horizontal beam widths and wide vertical beam widths, providing accurate horizontal angle determination with reasonable vertical distribution of energy over a wide range for consistent radar mapping qualities. [Ref. 56:p. 8]. An even distribution of energy over the ground allows the radar to present a more map-like display for wide ranges with fewer gaps where the radar is not illuminating [Ref. 56:p.146].

Up to this point, a very important shortcoming of all real antennas has been ignored. The effect is called sidelobing. When the desired main beam pattern is transmitted, additional patterns of similar shape but smaller amplitude are transmitted at intervals around the antenna in a three-dimensional pattern. Figure 2 shows the effect in two dimensions. All real antennas have this problem to some degree; although, the number of sidelobes and their intensity relative to the main beam vary with the quality of the antenna. The sidelobe pattern also typically changes when the antenna is installed on the airframe. Modern antennas greatly suppress the sidelobe problem with a decrease of from 20 to 100 db in the sidelobes from the main beam peak magnitude. A return from a sidelobe cannot be distinguished from a mainbeam return without special processing, and the azimuth of the sidelobe return appears to be that of the main beam return. [Ref. 56:p. 138].

A number of antenna scan patterns have been used for air-to-air and air-to-ground radars. Most modern radars use a gyroscopically or inertially stabilized, gimbal mounted antenna that allows the scan pattern to remain level with the horizon as the airplane is maneuvered [Ref. 56:p.24]. There is usually some maximum physical limit for displacement relative to the host aircraft, both horizontally and vertically. Since the antennas are normally mounted in the airplane nose, structural interference and RF interference with the airframe necessitates these limits. A limit of 60° left and right horizontally (azimuth) and 45° up and down vertically (elevation) are typical. A raster type antenna scan pattern is usually used. The raster scan moves horizontally left and right between the selected limits. Usually two or three angular widths are available for selection within the physical limits described above. Often the operator is also able to select the location of the center of the scan pattern, again within the physical limits described above. An operator would normally select a scan pattern less than the maximum limits and directed towards the target when the target bearing can be estimated. This provides more frequent scanning of the target area to reduce detection time. For air-to-air applications, the horizontal path is usually stepped up and then down by an incremental angular amount. Each horizontal scan is known as a bar and may be selected in number [Ref. 56:p.5], usually from one to four. Each bar typically overlaps slightly.

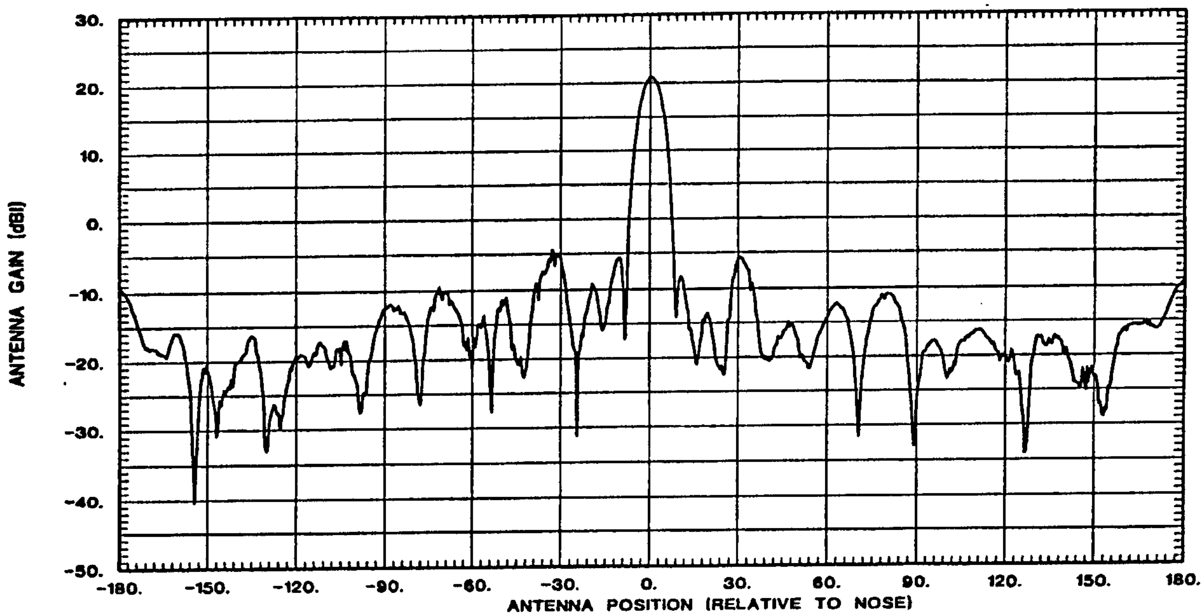

Figure 2: Two Dimensional Antenna Sidelobe Pattern

As the number of bars and the scan azimuth width are increased, the search volume increases and consequently the time between target illuminations increases. Increasing antenna scan rate can be used to counter this problem somewhat; however, if the scan rate is increased, the amount of time the target is within the antenna beam width, and thus the number of pulses illuminating the target per scan, is decreased. A tradeoff is necessary to optimize the number of hits per scan and to minimize the time between scans over the target. Usually the search volume is limited to that which can be supported by the radar and still be tactically useful. A multiple bar scan pattern is necessary to cover the search volume because a narrow vertical beam width is needed to allow altitude of the airborne targets to be determined. Knowing the vertical angle to the target (calculated in the same manner as the horizontal angle to the target) and the target range, a simple geometric calculation provides the target altitude relative to the host aircraft. This can be added to the host aircraft altitude to determine the target altitude.

Air-to-ground radars normally operate with a single bar scan pattern, and therefore the scan rate and scan angular width determine the refresh rate of the display. The number of hits per scan is maximized to maintain a consistent, map-like display and so the tradeoff is one of providing a quick scan rate to shorten the refresh period and a long one to keep the number of pulses over a given azimuth high enough to provide a consistent, map-like display.

The ideal, pulsed radar sends out the RF energy in discrete packages (pulses) of a specified duration. The pulse duration ideally has very rapid rise and fall times. It is assumed here that the rise and fall times are essentially instantaneous since modern radars come very close to achieving this goal. The pulse width defines both the theoretical minimum range and the theoretical minimum range resolution. The theoretical minimum range is defined in the following equation [Ref. 39:P. 2.7B]:

$$R_{min}=\frac{(C)(PW)}{2}$$
$$C = \textit{The speed of light or } 3 \times 10^8 \frac{meters}{second}$$
$$9.7125 \times 10^8 \frac{feet}{second} \qquad (1)$$
$$161{,}875 \frac{nm}{second}$$
$$R_{min} = \textit{theoretical minimum range}$$
$$PW = \textit{Pulse Width}$$

Any target closer than this range will not be observed since the duplexer will still be switched to the transmit side of the radar. The theoretical range resolution limit ($R_{min\ res}$ or minimum range resolution) is equal to the same value. [Ref. 39:p. 2.8a]. Since the return from the farther of two targets, that are closer together than the range resolution limit, will be received at the receiver coincident with that of the nearer target and will thus be unresolvable without additional information (discussed later). From these considerations a short pulse width is desirable; however, a long pulse width is needed because energy is transmitted only during the duration of the pulse and the average power illuminating the target increases as the pulse width is increased. This increases the probability of detection, all else being equal. [Ref. 56:pp. 159-160].

The number of times that the pulsed radar transmits its pulse per second is known as the Pulse Repetition Frequency (PRF). PRF determines the maximum theoretical unambiguous range. The radar waits between transmissions for return pulses. If the PRF is too high, and thus the time between pulses is too short, the return from a previous pulse will return while the radar is waiting for the return from a more recent pulse. The time interval between pulses is called the Pulse Repetition Interval (PRI). The radar would be unable to determine which transmitted pulse the returns were associated with, and some returns would be associated with the incorrect time slot. [Ref. 56:pp.157-158]. Conversely, the PRF must be kept as high as possible to increase the average power out of the radar and thus the probability of detection. There are methods for resolving ambiguities between interpulse periods. The simplest is merely to vary the transmitted RF frequency from pulse to pulse, correlating a return pulse with its associated transmitted pulse by matching frequencies. [Ref. 39:p. 2.8]. For a simple pulsed radar without special techniques applied, the theoretical unambiguous maximum range is defined as [Ref. 39:p. 2.8b]:

$$R_{max\ unamb}=\frac{(C)(PRI)}{2}$$
$$R_{max\ unamb} = \textit{theoretical unambiguous maximum range} \qquad (2)$$
$$PRI=\frac{1}{PRF}$$

Frequency can affect the maximum range of the radar since some frequencies are impacted by molecules and particles within the atmosphere more than others. The impact is a function of the wavelength of the radar RF frequency relative to the diameter of the various particles and molecules in the atmosphere. The effect can be dramatic. Wavelength is related to frequency by the following expression [Ref. 56:p. 125, Ref. 27:pp. 5-1.1-5-1.3]:

$$C=f\lambda$$
$$C = \textit{speed of light} \qquad (3)$$
$$f = \textit{frequency in hertz}$$
$$\lambda = \textit{Wavelength in meters, feet, etc. as appropriate}$$

Some frequencies propagate through the atmosphere with less absorption than others. At the frequencies most used for air-to-air and air-to-ground radars, oxygen and water molecules are the greatest absorbers of RF energy [Ref. 56:p. 125, Ref. 27:pp. 5-1.1-5-1.3]. Lower frequencies can actually propagate beyond the horizon by bouncing downward in the upper atmosphere, bouncing up from the ground and/or by conforming somewhat to the curvature of the earth [Ref. 36:p. 2.80]. Air-to-air and ai[illegible] to-ground radars are generally w[illegible] above this frequency since the lo[illegible] frequencies require large antennas (most antennas are optimized at multiples of 1/2 the RF wavelength). Virtually all the radars that fall in the categories discussed here radiate at between 6 GigaHertz (GHZ) and 18 GHZ. At these frequencies moisture content of the atmosphere has an effect because of the wavelength relative to the water molecule's size. Also, these frequencies propagate essentially on a straight line path, that is, along the line of sight. [Ref. 36:p. 2.80]. Above the 20 GHZ level, the atmosphere absorbs virtually all the RF energy at short ranges [Ref. 36:p. 125].

The tools have now been presented to analyze one of the most crucial features to be evaluated on a new radar. This parameter is the maximum detection range of the radar (not the same as the maximum unambiguous range). This characteristic receives much attention during a test program because it is often the performance feature by which radars are compared and measured. Reference 36 provides a good derivation of the radar range equation which is presented here without proof [Ref. 39:pp. 2.12-2.15]:

$$R_{max}=\left[\frac{PG\sigma A}{(4\pi)^2 L\ k\ T\ B_n F_n\left(\frac{S}{N}\right)_{min}}\right]^{\frac{1}{4}} \qquad (4)$$

P=Transmitted power of the radar.

G=Directive gain of the antenna, a measure of the ability of the antenna to direct the RF along a straight line rather than transmit it evenly around the antenna in a spherical pattern (isotropically).

σ=The radar cross section of the target. "The radar cross section of a target is that area which, when multiplied by the radar signal power density incident upon the target, if radiated isotropically by the target, would result in a return back at the radar equal to that of the actual target" [Ref. 39:p. 2.16]. Simply, the radar cross section is a measure of the ability of the target to reflect radar energy. The radar cross section varies with the specific frequency, and thus wavelength, and changes, sometimes dramatically, as the angle of incidence upon the target changes [Ref. 39:p. 2.17, Ref. 28, Ref. 8, Ref. 44:pp. 89-127].[4]

A=The radar antenna capture area.

L=A loss factor which accounts for non-specific losses within the radar receiver.

$(k)(T)(B_n)(F_n)$=All are related to the interference within the system caused by thermal noise. Thermal noise is a function of the absolute temperature of the system and the band width of the system. Most modern radars have come close to optimizing this set of parameters; and, as such, there is little room for improvement for the designer.

$(S/N)_{min}$=The Signal to Noise ratio is a measure of the signal strength divided by the noise received. The minimum signal to noise is that S/N that can just barely be identified as an actual target. The $(S/N)_{min}$ depends on many factors, most of which can only be defined poorly. Operator experience and the accepted false alarm rate are examples of these variables.[Ref. 14:p. 2.15]. Modern radars can have an $(S/N)_{min}$ well below unity using advanced processing techniques to pull the target's returned energy out of the noise level. Some will be discussed later.

Note that the entire expression is raised to the 1/4 power. Improving any one factor by 16 will only double the radar range. [Ref. 39:p. 2.15]. σ is a function of the target and not under the control of the radar designer. $(k)(T)(B_n)(F_n)$ are only slightly under the control of the designer since some thermal noise must exist in any real system and most modern systems handle this problem fairly well. L is very close to unity in many modern systems and; therefore, cannot affect the order of magnitude changes necessary to significantly increase the radar range. A is limited by the frontal cross sectional area of the airplane nosecone which is where most radar antennas are housed. [Ref. 56:p. 127]. This leaves P,G and $(S/N)_{min}$ for the designer to manipulate and affect maximum range.

Peak power out is usually limited by the physical weight and size of transmitters that have to be carried in airplanes. Lowering peak power reduces airplane weight. [Ref. 56: p.124]. A pulsing scheme has to be worked out to lower peak power while optimizing average power over time [Ref. 56:p. 159-160]. Generally, some modulation scheme of either frequency or PRF is used to allow increasing the pulse width or PRF to effect greater average power while at the same time not sacrificing other radar parametric performance. Some of these techniques are described later. Increasing average power can cause other problems. As power output is increased, the probability of the signal being received by the enemy and exploited is

[4]Knott, Shaeffer and Tuley, reference 28, is the best volume on radar cross section I have read to date. It also includes a truly outstanding discussion of radar cross section reduction techniques. This is a must reference for all concerned with testing modern air-to-air or air-to-ground radar systems.

increased [Ref. 39:p. 2.12-2.13]. Since the signal path to the enemy receiver is only a one way path, the radar range equation dramatically shows the importance of keeping the power levels within limits. One technique makes use of the ambient noise level to hide the transmitted RF.

Antenna Gain is improving at a slow but steady rate. Most modern radars rely on slotted array planar antennas which are a pattern of slot shaped antennas aligned in a flat plane. These planar arrays achieve a G of as much as 40 db in current production systems. The minimum signal to noise ratio can be improved by increasing the sensitivity of the receiver while at the same time improving the capability to reject ambient noise. Rejecting noise keeps the false alarm rate down. Many techniques involve modulating the transmitted signal in a unique fashion not duplicated in nature to allow the receiver to differentiate between the return signal and noise. The power density can be spread out to a lower level than the ambient noise and then pulled back out at the receiver. This is possible because a pseudo-random code known only by the transmitting radar is used to modulate the RF. The code must be known to pull the signal out of the noise. The signal is almost impossible to detect without the code since the pseudo-random modulation makes it look like noise. This technique is finding application in a large number of current and developing communication and radar systems. [Ref. 36:pp. 2.108-2.111].

2.1.3. Doppler Radars

The operating principles of doppler radars are based upon the fact that RF reflections from a target that is closing in range radially along the direction of propagation are shifted up in frequency, and reflections from a target that is opening in range are shifted down in frequency. This phenomenon is demonstrated in the audio spectrum by a train passing with the horn sounding. The horn sounds higher in frequency as it is approaching and then lower in frequency as it is receding. [Ref. 56:p. 9, Ref. 27:pp. 2-2.1-2-2.5]. It must be emphasized that this measurement is limited to radial velocities only [Ref. 56:p. 9, Ref. 27:pp. 2-2.1-2-2.5]. A target could be moving hypersonically, perpendicular to a non-moving doppler radar, and it will exhibit a zero doppler shift. Another point to note is that a doppler shift is also imparted by ownship motion. For example, ground clutter directly along the flight path of the airplane will tend to exhibit a doppler shift equal to the groundspeed of the airplane [Ref. 13:p.2.36, Ref. 27:pp. 2-2.1-2-2.5]. Several techniques are available for eliminating doppler shift due to ownship motion. The simplest technique is merely to filter out all doppler shifts around the ownship groundspeed motion induced doppler value along the radar boresight [Ref. 56:p.9]. This technique is often used in air-to-air radars.

A number of techniques have been devised for detecting targets that are moving with respect to ground clutter. These systems are known collectively as Moving Target Indicators [Ref. 39:p.2.48] or in the case of airborne radars as Airborne Moving Target Indicators (AMTI) [Ref. 39:p.2.29]. One class of AMTI radars uses only the doppler effect to detect moving targets. These radars use very long pulses to increase the average power and consequently cannot determine range to the target. In this situation, the only reason pulsing is used is to allow the same antenna to be employed to transmit and to receive. Target bearing is found as in pulsed radars. The high average power and sensitivity to closure rate make these radars ideal for gaining relatively long range detection on high closure rate targets. The high average power output improves small σ target detection (the increase in P compensates for a small σ in the radar range equation). The rejection of ground clutter based upon the ownship motion doppler shift filtering described above also increases the probability of small target detection in the clutter. All these effects make the doppler mode of operation ideal for the detection of small, low flying cruise missiles closing on the radar.

Several doppler radar parameters affect the performance of the system. One parameter is the accuracy with which the doppler shift (frequency change between the transmit and receive signal) can be measured. This accuracy directly relates to the ability of the radar to discern between two targets close together in bearing and also close together in closure speeds. As the difference in doppler shift approaches a value equal to the doppler shift accuracy, the targets become unresolvable in closure speed. The uncertainty in doppler frequency shift is directly convertible to a closure rate uncertainty. [Ref. 39:p.3.18].

2.1.4. Pulse Doppler Radars

Pulse doppler radars combine the ranging capabilities of the pure pulsed radar with the closure velocity determination capability of the doppler radar. With this technique, doppler shift measurements are applied within the pulse width of the transmit and reply signal providing the best of both radars, although not without added complications. All of the performance limitations of both pulsed radars and doppler radars apply; however, the pulsing of the doppler RF adds several new limitations. The first is caused by the effects of frequency folding or aliasing. [Ref. 39:p. 2.34].

The pulsed radar is essentially a data sampling system and, as in any sampling system, "the sampling process creates new frequencies, other than the desired transmit frequency, which replicates the desired spectrum in the frequency domain, at intervals equal to the sampling rate" [Ref. 39:p. 2.34]. The sampling rate is equal to the PRF for radar applications [Ref. 39:p. 2.34]. The return signal replicates itself at a lower power level, at multiples of the radar PRF [Ref. 39:p. 2.34b]. As described, this effect occurs for a simple sinusoidal signal and becomes even more complicated if the signal is further modulated as are most radar signals. Since the doppler portion of the pulse doppler radar measures the frequency change of the transmitted RF, this problem is serious and results in ambiguous doppler shifts, and thus ambiguous radial velocities, at each frequency fold. [Ref. 39:p. 2.35]. The solution to the problem is to select a PRF high enough such that the first frequency fold occurs at a doppler shift, and thus a closure speed, higher than of interest to the operator. In a pulse doppler system this is contrary to the requirement of having a low PRF to prevent range ambiguities. A tradeoff occurs in these radars between low/high PRF and thus range ambiguities/closure rate ambiguities. The best solution depends upon the intended use of the radar. [Ref. 39:p. 2.42].

Another problem results from the effects of ground clutter returns on various portions of the radar transmission pattern. Since all real radar antennas have antenna patterns with sidelobes outside the main radar beam, ground clutter returns are of three different types. The highest amplitude return is caused by the main beam itself and is due to the doppler shift from ownship motion along the radar line of sight. Along with this return is a return which is much wider in its frequency spectrum and lower in power caused by clutter in the radar sidelobes. Finally, a narrow frequency spike occurs at the transmit frequency due to the return from the ground immediately below the aircraft. This is called the altitude return. The entire spectrum is illustrated in figure 3 [Ref. 39:pp. 2.35b-2.36].

Without further processing, the target return would have to be strong enough to break out of the clutter and noise combination. It is very unlikely that a small target would be seen within any of the clutter pedestals described. A common method of handling this problem is simply to filter out all of the main beam, altitude return and sidelobe clutter pedestals, requiring the target to only break out of the noise [Ref. 39:p. 2.37]. Unfortunately, this eliminates a wide spectrum of closure rates where the target would not be seen, but leaves few false alarms. Other radars leave the sidelobe clutter pedestal. The effect is fewer excluded closure rates but a lot of noise in the sidelobe clutter pedestal for the radar and/or the operator to sift through. The target return must be strong enough to be seen inside the pedestal [Ref. 39:p. 2.37] and the false alarm rate is usually increased. Fortunately, other methods have been devised for dealing with clutter. One will be discussed here as an example. Delay Line Cancelers (DLCs) allow the radar to save the return pulse from one PRI to another and then to pass the two through a filter. The two are essentially subtracted from each other and the difference is due to changes over time, that is, motion over the ground clutter.

When using the simple method of subtracting out the clutter pedestals, there are resultant blind speeds, around the speed of ownship, along the radar line of sight. This problem is complicated when frequency folding occurs since this leaves one blind closure rate for each fold. When using DLCs, there is a minimum speed over the ground clutter that the target must make for the DLC circuitry to be able to discern a minimum resolvable change from pulse to pulse. This means there is also a minimum resolvable closure rate. DLCs are also susceptible to frequency folding just as in other pulse doppler systems and thus these minimum doppler shift closure rates may be repeated at

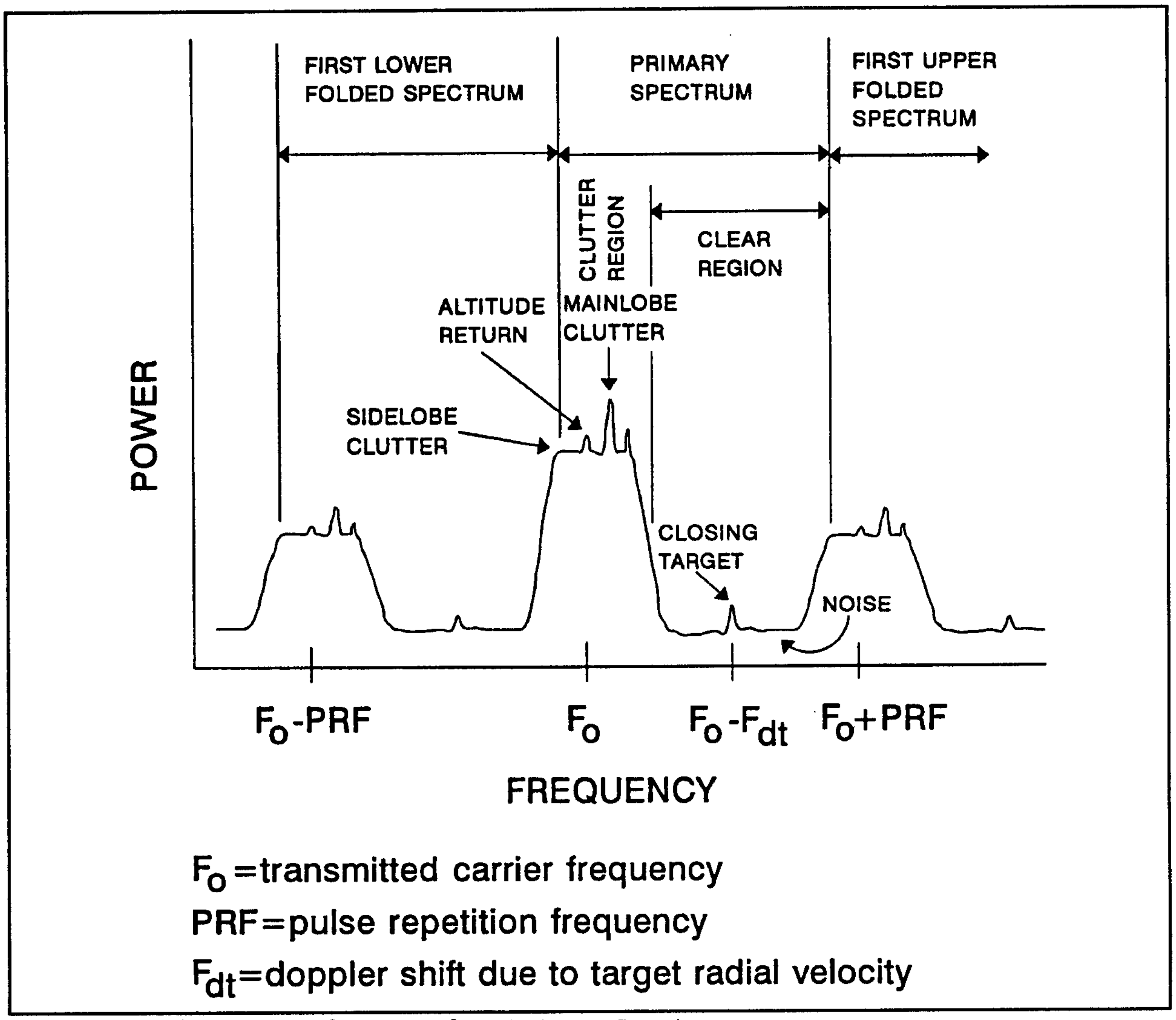

Figure 3: Airborne Pulse Doppler Return Spectrum

intervals over the velocity spectrum. [Ref. 56:pp. 425-426].

2.1.5. Advanced Techniques

2.1.5.1. Pulse Compression

The first advanced technique to be discussed is pulse compression. In pulse compression, the transmit pulse is generated with a spread of frequencies within a defined band. The pulse is then passed through a filter, called a Dispersive Delay Line (DDL). The effect of the DDL is to arrange the RF within the pulse such that the lower frequencies are transmitted at the beginning of the pulse width, linearly increasing to the higher frequencies by the end of the pulse width. The return pulse is then passed through the same filter in the opposite direction, which slows the lower frequencies in the lead and by the end of the pulse applies no delay. The effect is to stack the return pulse. The result is to provide better range resolution from the narrow processed pulse width with the benefits of high average power from the wide transmit pulse. Typical compression ratios are around 100/1. [Ref. 56: pp. 217-218]:

$$compression\ ratio = \frac{transmitted\ PW}{compressed\ PW} \qquad (5)$$

$$PW = pulse\ width$$

2.1.5.2. Doppler Beam Sharpening

The next technique to be discussed is Doppler Beam Sharpening (DBS). DBS has found application mostly in air-to-ground radars. As the radar antenna is scanning, the antenna boresight moves from side to side. The ground target doppler shift is a measure of the component of the host airplane's velocity along this boresight. All fixed ground targets have a doppler shift caused by the geometric component of own aircraft motion along this boresight. For these reasons, as the antenna scans, the ground return doppler shift will change by a predictable amount. DBS makes use of this concept by measuring the doppler shift of the ground returns and comparing them to the doppler returns for adjacent returns in azimuth to determine very precise angles off of the aircraft ground track. The result is a very precise angular determination for target returns, much better than the antenna beam width. Unfortunately, the doppler shifts vary slightly from pulse to pulse around the theoretical value and the information must be integrated over time to get the true value. A lot of radar information must be stored to display the entire search volume and the display often requires 10 to 15 seconds to build. The data is normally stored in small angular and range bins within the radar computer and the display usually appears like small building blocks of varying intensity. A lot of computer memory and processing time is required for this process.

Since DBS only affects angular resolution, some technique is needed to improve range resolution consistent with the angular improvement. This is usually accomplished merely by decreasing the pulse width of the transmit signal enough to provide a harmonious balance of angular and range resolution. The reduced pulse width also reduces average power and in turn reduces the maximum DBS range to 40 or 50 nm. Another limitation of DBS is caused by the geometry of the technique. The doppler shift change close to the radar ground track is very small as the radar sweeps, increasing by the cosine of the angle off of the ground track to a maximum as the perpendicular position is reached. A minimum discernable change is required to be resolvable, causing a small notch, usually 7° to 15° wide, over the nose of the airplane, where the DBS picture is blanked. In some radars, this is filled, with limited success, with real beam radar video. Most state of the art DBS radars can provide a map like display with an order of magnitude improvement in resolution within the constraints discussed above. [Ref. 56:pp. 2.66-3.29].

2.1.5.3. FM Ranging

As discussed above, the more continuous the transmission pattern, the higher the average power out and the longer the maximum detection range. The drawback of extremely long pulse widths is that ranging of the target becomes impossible. Frequency Modulation (FM) ranging provides ranging data even with very long or continuous pulse trains. In FM ranging, the pulse train is ramped linearly up in frequency to a peak from some baseline frequency and then linearly ramped down to the original baseline. This pattern is repeated at intervals roughly equivalent to conventional pulse repetition intervals. The return pulse is then compared to the transmitted pulse to find the peak, providing a time reference from which to determine the time of propagation to the target and back. Instead of measuring the time from transmission to receipt of a discrete pulse, the time from transmit to receipt of the peak is measured, providing range. [Ref. 39:pp. 2.29-2.32]. In practice, this technique is much less accurate (by as much as an order of magnitude) than pulse ranging and has poor resolution, but reasonable ranges can be determined for the long range targets that the wide pulse width radars are designed to detect. The reduced range resolution and accuracy are a result of the inherent inaccuracies associated with determining the precise point of the frequency peak. [Ref. 56:pp. 239-240].

2.1.6. Displays

Two types of display formats have found application in most modern air-to-air and air-to-ground radars. The most widely used, and most versatile, is the Plan Position Indicator (PPI) format. In this format, the sweep emanates from a single point, usually the bottom center of the scope, and describes a slice of a circle with radius equal to the sweep length. The origin of the sweep is the ownship position and the target's position relative to ownship is measured as the bearing of the sweep and range from ownship. [Ref. 56:p. 25, Ref. 27:pp. 5-5.3-5-5.6]. Since a pure bearing/range format from ownship is used, the display closely resembles the real world. That is, if a mapping mode is being used, the radar display will resemble the real world. The bearing and range measurements are made as direct line of sight measurements and as such do involve some slant range errors. These errors account for slight distortions at short ranges. Another short range distortion is caused by the very shape of the display. Since the display comes to a notch near ownship, targets near the notch of the V are very cluttered, and as such, resolution generally suffers very close into ownship. Both of these short range display problems can affect the minimum usable range of the radar and can cause it to be greater than the theoretical value described earlier.

Some applications require a quick and accurate representation of target bearing and range more than the map like picture described above. One application is in fighters, where accurate target angle and range information is required to set up and execute intercepts. For these purposes, the B scan format display has found application. B scan displays are set up with range on the y axis and angle to the target on the x axis [Ref. 56:p. 25, Ref. 27:pp. 5-5.3-5-5.6]. This format is more a display of information rather than a picture of the real world. The effect is to "spread the world out" at short ranges, distorting the picture. The B scan has limited application in the air-to-ground arena, although some applications exist. Air-to-ground B scan applications are usually limited to small area displays offset from ownship (patch map) [Ref. 56:p. 25]. DBS often uses a B-scan format to facilitate conversion from memory storage in the range and azimuth bins to display. Velocity Search (VS) modes are displayed with angle to the target on the x axis and closure rate on the y axis [Ref. 39:p. 3.26]. Figure 4 includes samples of several display formats.

Display resolution is important in all display formats. Often the display has less resolution than does the radar system. As a result, a lot of good radar system design work suffers. Cathode Ray Tubes (CRTs) are used in most displays today. These displays have a fairly well defined resolution based upon the number of raster lines per inch, or the number of resolvable points per inch that are displayable. This number is applicable to both dimensions on the display. Knowing the selected range scale, the theoretical resolution limit can be determined.

$$\textit{display resolution} = \frac{(\textit{scale in nm/in})}{(\textit{raster lines per display inch})} \qquad (6)$$

For the digitally driven CRT digital displays in use today, the presence or absence of a target is usually easily interpreted by the operator. For the old analog displays still in use, display quality, system set up and operator proficiency can greatly affect nearly every radar parameter.

2.1.7. Analog Versus Digital Displays

Almost all new radar system displays are implemented in a digital format. This means that analog to digital conversion of the radar return takes place and some amount of radar processing is used before the information is displayed to the operator. The benefit is a cleaner display gleaned from the chaos of the analog world with only the necessary information making it to the display. Decreasing the unusable information from the display tends to reduce operator workload. This is perhaps the major advantage of the digital format. The displays are clean and target presence is easy to determine. The major disadvantage of the digital format is that in paring out the clutter, the system often deletes usable information. Analog displays leave everything for the operator to interpret himself. For this reason, a skilled operator with time to concentrate on the analog display can almost always out perform a digital system. The disadvantage of analog is the time and concentration required, which distracts the operator from making tactical decisions.[Ref. 27:pp. 5-5.1-5-5.2]

2.1.8. Radar Tracking

Two types of air-to-air radar tracking modes are common to modern radars. The first, Single Target Tracking (STT), is implemented by concentrating the radar on a single, selectable target and using the output to determine target parameters. For a ranging mode, this includes the target's range, bearing, course, groundspeed and altitude. The antenna is typically pointed at the target and a feedback process is used to determine the target parameters. For a VS mode, the target's bearing and closure rate are tracked. [Ref. 39:p. 2.55]. The advantage of an STT mode is that the course and groundspeed can be determined for a pulsed mode and also the radar is concentrated on a single target, increasing the detection level. STT is typically selected when a target is chosen for intercept and intercept

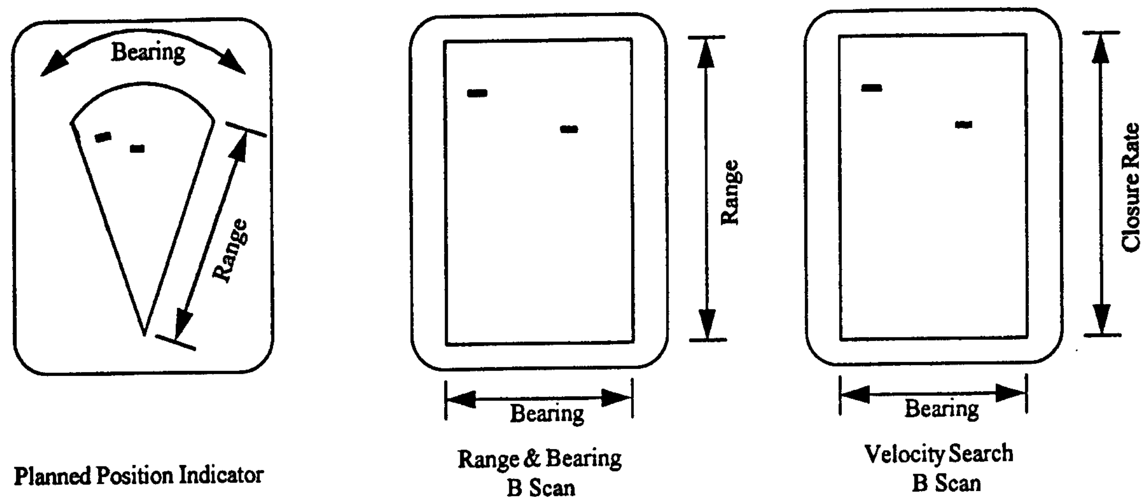

Figure 4: Sample Display Formats

calculations and display formats are usually provided.

The second air-to-air tracking mode, Track While Scan (TWS), allows the radar to continue to detect targets within the search volume while determining track parameters (course, speed and altitude) on some number of tracks within the same search volume. The antenna continues to scan and the radar saves the detected target parameters from each scan, using the information to determine a bearing, range, course, groundspeed and altitude on the targets. The advantages of TWS are increased Situational Awareness (SA) outside of the area of the target being intercepted, while still calculating target course, groundspeed and altitude. The disadvantage of TWS is that the detection level for individual targets is reduced from the STT level. [Ref. 39:pp. 2.61-2.62]. The number of possible track files varies with the individual radar.

For air-to-ground radars, geographically stable cursors for designation of ground targets are common. The cursors, which may take the form of cross-hairs or brackets on the display are placed over the target by the operator. The position of the cursors are stabilized geographically by the navigation system of the airplane [Ref. 39:p. 3.27]. The cursors stay stationary relative to the radar video. Unwanted motion in the cursor is a result of navigational drift, causing the cursors to move relative to the radar video. The cursors are used for designating a target position for use by the fire control computer, for navigation updates, etc.

2.1.9. Missions

A radar is designed for a specific mission and testing procedures have to be tailored and the results analyzed to reflect emphasis on the parameters important to the mission. For military radars, these missions are often explained in a general way in the individual aircraft detailed specifications, Test and Evaluation Master Plans (TEMPs), etc. These documents tend to be vague. For this reason, when designing tests and in analyzing the results, it is essential that the evaluator have an in depth knowledge of the intended use and expected environment. Operational experience in a similar platform is not essential but extremely helpful. If this experience is not available on the test team, extensive research is called for. As an example, the choice of targets for air-to-air testing should always reflect the intended threat. An interceptor designed to defend against large, long range, strategic bombers would require a different target than a fighter designed to defend an attack group against other small, agile fighters. The target should reflect the intended use and in fact many new detailed specifications are written with this in mind, in that the detection/tracking sections are written in terms of targets that are similar in radar cross section and performance to the threat. Many other examples are possible. The concept is often called "mission relation" and is applied to the test design, data analysis and in the justification of the final results.

Mission relatable tests are particularly important in the test techniques presented here. Since these techniques are designed to provide a quick/inexpensive assessment vice an in-depth engineering analysis, there is not much time to completely cover a plethora of data points. The important data points have to be acquired in a mission relatable scenario and the analysis has to reflect this mission relation. As an example, when doing maximum detection range tests, the designing engineer would desire an in-depth set of detection data over a wide variation of environmental conditions (i.e.: low/high clutter, visible moisture/clear weather, wide closure speed range, etc.) From an engineering standpoint, this allows the engineer to be able to see the effects of extremes of the possible variables; however, it may tell little about how the radar will perform in its intended environment. This is the goal of the techniques presented here. Money and time can often limit the number of data points per test to one or two. A mission relatable target in a scenario that reflects the intended use of the radar is required. The evaluator must understand the mission before designing the test, and must test to the mission.

2.1.10. Radar Systems Human Factors

No attempt will be made here to completely cover the topic of human factors; however, the introduction of a few concepts specifically applied to airborne radar is in order. First, anthropometric data and the concept of the Design Eye Position (DEP) must be discussed.

In 1964 a study of 1,549 Naval Aviators was performed to obtain 96 body measurements [Ref. 66]. Items such as weight, height, height from the seat to the eyeball position, reach length, etc., were collected for a wide group of aviators and then statistically analyzed. The outcome of the study was a definition for each parameter of the average measurement and measurements below which various percentages of the group would fall. Most aircraft specifications are written to require the 3 to 98 percentile group (measurements that are at least as great as the lowest 3 percent and lower than the upper 2 percent) to be able to manipulate and use all the furnishings, controls and displays in the cockpit [Ref. 47:pp. XV3-XV4]. As an example, most cockpit seats are designed to be adjustable up and down over a certain range. The center of this range is almost always optimized to accommodate the average, or 50 percentile individual, described above, and the upper and lower limits are almost always designed to accommodate the 3 and 98 percentile persons.

There is an eye position within the cockpit for which all the cockpit controls and displays are optimized. The range of seat adjustments described above are designed to allow placing the eye of the 3 to 98 percentile persons at this position. This is called the Design Eye Position (DEP). [Ref. 47:pp. XV4-XV5]. This is the point from which all control and display tests should be performed. The DEP is usually close to the midway seat position for the 50 percentile person. The correct seat position to place the evaluator's eye at the DEP can be approximated by placing the seat at the center of the range of adjustment and finding the evaluator's anthropometric sitting eye height and the 50 percentile sitting eye height from the anthropometric data tables. The two can then be subtracted and for the taller person the seat can be moved down by the difference to drop the evaluator's eye to the correct position. For the shorter person the seat is raised by the difference. While wearing a standard flight helmet, the head is placed against the head rest. The evaluator's reach is defined while the head is placed at this point.

Controls and displays should be evaluated while seated at the DEP and wearing normal flight clothing. A complete set of anthropometric data should be collected on each evaluator and the measurements documented in all reported test results. A deficiency with control reach is meaningless when the cockpit was designed for a reach range that does not include the evaluator. The clothing and personal flight equipment worn should also be documented.

A good discussion of the specifics of human factors standards applied to radar displays and controls can be found in references 13 and 14.

2.1.11. The Sample Radar System

The sample radar used to illustrate the development of the basic radar test techniques is a multimode air-to-air and air-to-ground radar installed on a modern fighter/attack airplane. The air-to-ground radar modes include real beam map as well as DBS modes. Geostable cursors with digital displays are available. The air-to-air radar modes include pulse compressed, VS and FM ranging. The radar will operate in either search or TWS air-to-air modes.

2.2. AIR-TO-AIR AND AIR-TO-GROUND RADAR TEST TECHNIQUES

2.2.1. Preflight and Built-in-Tests

2.2.1.1. Purpose

The purpose of this test is to assess the suitability of the radar preflight and turn on procedure and the Built-In-Test (BIT) to quickly and easily bring the radar on line and insure an operational or "up" system, once airborne.

2.2.1.2. General

As airplanes become more expensive, fewer and fewer will be available to accomplish each mission, amplifying the loss of individual airplanes to inflight failures. Quick, accurate ground preflight tests are essential to determine system status while repairs can still be performed. A quick response/alert time is also important and so these checks must be expeditious and must allow the operator to prepare for the mission with a minimum of distractions. Limited airplane availability also implies the need for quick turn-arounds to send the same aircraft out for successive missions. This necessitates a very short preflight and turn on procedure that can be accomplished safely and thoroughly before a hurried combat mission.

2.2.1.3. Instrumentation

A stop watch and data cards are required for this test. A voice tape recorder is optional.

2.2.1.4. Data Required

Qualitative comments, time to complete the preflight/turn on and time to complete the BIT is required. A record of BIT indications are required.